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Geotechnical Aspects of Rock Erosion in Emergency Spillway Channels

Supplemental Information on Prediction, Control, and Repair of Erosion in Emergency Spillway Channels

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GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
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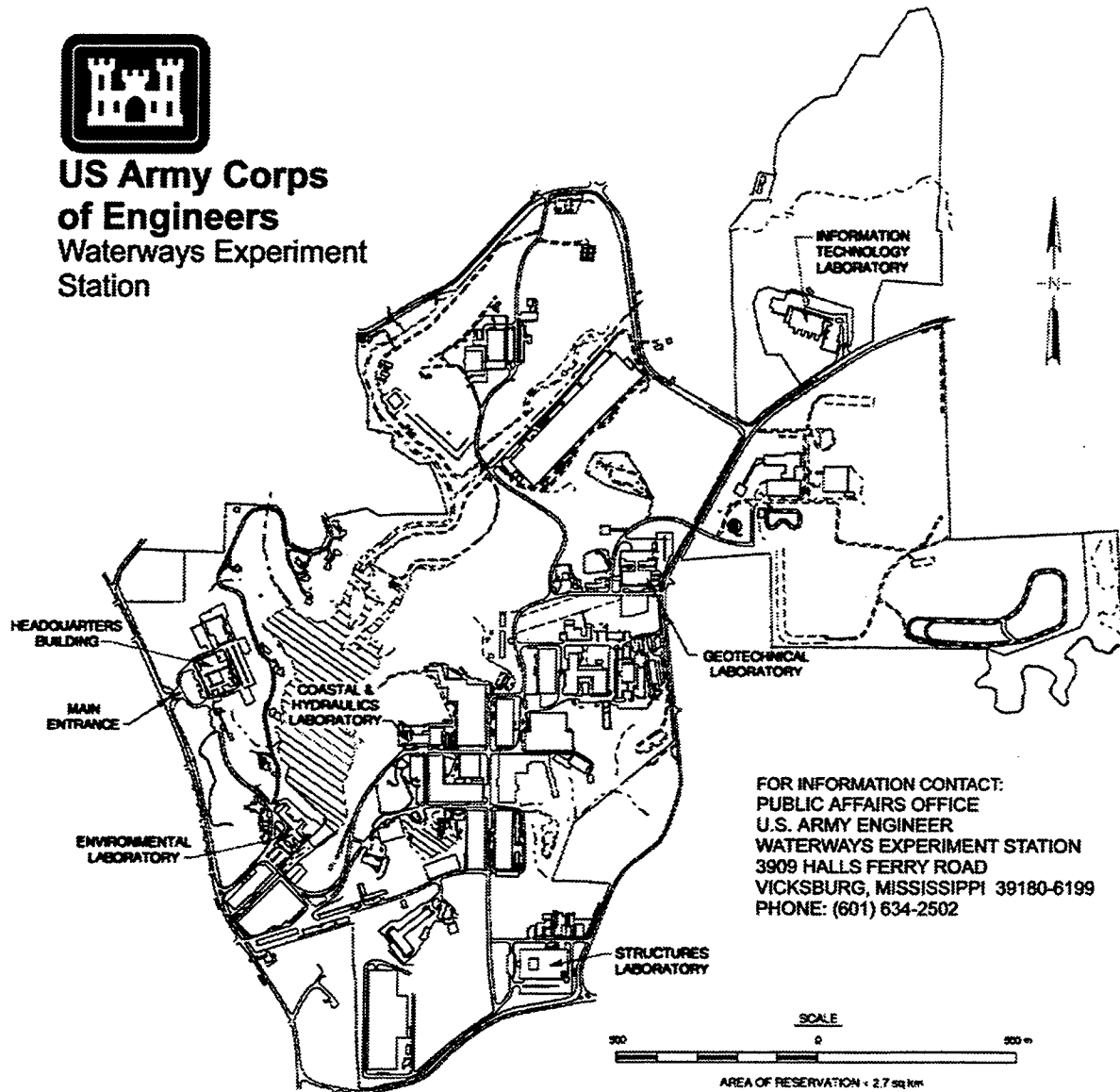
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Preface

This study addresses the geologic factors that control rock erosion in emergency spillway channels, develops a technique to evaluate the risk and predict the potential erosion of rock and soil exposed to hydraulic attack during a flow event in the channel, and provides design concepts for the repair and rehabilitation of spillway erosion. The study was conducted under the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The REMR Program Manager was Mr. William F. McCleese, Structures Laboratory, WES. Mr. Mike Klosterman (CECW-E), Headquarters, U.S. Army Corps of Engineers, was the Technical Monitor.

This work was conducted under the direct supervision of Mr. J.S. Huie, Soil and Rock Mechanics Division (SRMD), and Dr. James H. May and Mr. John B. Palmerton, the Principal Investigators, Earthquake Engineering and Geophysics Division (EEGD), Geotechnical Laboratory (GL), U.S. Army Engineer Waterways Experiment Station (WES). General supervision was provided by Mr. Joe L. Gatz, Chief, Engineering Geology Branch; Dr. A.G. Franklin, EEGD; Dr. D.C. Banks, SRMD; and Dr. W.F. Marcuson III, Director, GL.

Most of the data for this research came from two Federal agencies: the U.S. Army Corps of Engineers (CE) and the U.S. Department of Agriculture, Soil Conservation Service (SCS). Drs. Dave Patrick and Chris Cameron, of the University of Southern Mississippi, contributed many hours of helpful discussion. Messrs. Dave Ralston, Lou Kirkaldie, John Brevard, John Moore, and Jim Hyland of the SCS were extremely supportive by opening their files and providing constructive feedback on ideas and written reports. Messrs. Darrel Temple, Kerry Robinson, and Gregg Hanson of the Agricultural Research Service - Hydraulic Structures Laboratory furnished many new insights and observations concerning spillway erosion. This report draws heavily from the doctoral dissertations by Dr. May and Dr. Kerry D. Cato, completed under the supervision of Dr. Christopher C. Mathewson, Director, Center for Engineering Geosciences and Professor of Engineering Geology at Texas A&M University, College Station, TX.

At the time of the publication of this report, Dr. Robert W. Whalin was Director of WES. The Commander was COL Robin R. Cababa, EN.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
inches	25.4	millimetres
pounds per cubic foot	27.6799	grams per cubic centimetre
pounds per square inch	6.894757	kilopascals

1 Introduction

Objectives and Approach of Study

The technology and methodology to evaluate erosion in emergency spillway channels are in their infancy with only recent detailed case histories providing a foundation; no synoptic study of case histories or theoretical basis of soil and rock erosion exists. Current methods are not applicable to most spillways in which material conditions range from loose soil, to slightly indurated soil, to weathered rock, and finally to massive, unfractured unweathered rock. Only erosion of loose sediment has been studied in detail. This study is a synoptic approach that uses case histories of emergency spillway erosion to determine the effects of wide ranges of geologic materials on the erosion process.

The goal of this study is to determine which geologic factors are the most useful predictors of emergency spillway channel erosion, to use them to develop a technique to predict erosion potential in emergency spillway channels, and to establish design concepts for channel design and erosion repair projects. This objective was achieved through the following subobjectives:

- a.* Assessment of erosion damage at sites that have received flows through an analysis of the geometric, hydraulic, and geologic conditions affecting site performance using postflow surveys and observations.
- b.* Determination of geologic characteristics of the spillway channel foundation by reviewing construction data and through observation.
- c.* Development of a geologic erosion equation by assessing the effect of various geologic factors on spillway channel erosion.
- d.* Combining geologic equation with the geometric and hydraulic factors to develop an erosion potential technique.
- e.* Establishment of design concepts and recommendations for the design and repair of erosion in emergency spillway channels.

These objectives were fulfilled through the following approach:

- a. Determining erosion damage at spillways that have experienced flows through the use of observations and postflow surveys to identify where damage was concentrated in the channel and describe the damage.
- b. Determining the geologic site conditions using construction data and observations including the construction of geologic cross sections parallel to the longitudinal channel profiles, the identification of the nature of each geologic erosion equation component, and the recording of any geologic influence on erosion not addressed in the equation.
- c. Explaining the effect of each geologic erosion equation component on the erosion performance for each site, and if the erosion could not be explained by the existing factors, define new factors which accounted for the erosion.
- d. Synthesizing the influence of each component of the geologic erosion equation for all sites.
- e. Developing conceptual designs for the repair and rehabilitation of eroded spillway channels.

Problem Statement

Significant numbers of excavated, earthen-floored emergency spillway channels are currently used at a large number of small dams and at a moderate number of large dams in the United States. These channels are excavated into all types of rock and soil and, unlike service spillways which may flow with greater frequency and hence have more erosion protection, are designed to flow rarely and experience minor erosion (U.S. Army Corps of Engineers (USACE) 1965). However, erosion-producing flows over the past 10 years have resulted in a need for maintenance and redesign of many emergency spillway channels. These spillway performances indicate that little is known about how to predict *in situ* soil and rock resistance to hydraulic stresses.

Emergency spillway erosion will become a greater problem as more dams experience spillway flows. The greatest probability of spillway flow appears to occur within the first 50 years of the life of a dam. Relating the number of operating dams to spillway flow events indicates an alarming trend. Consider, for example, the buildup of large dams after World War II. Approximately 2,000 dams existed in 1946, but by 1986 this number almost tripled to 5,450 (American Society of Civil Engineers/U.S. Committee on Large Dams (ASCE/USCLD) 1975, 1988). It is unknown how many large dams have earthen-floored spillways, but it is known that use of excavated spillways is common practice with earth- or rock-fill structures; 83 percent of all dams operating in 1986 were earth- or rock-fill dams. In 1946 historical spillway flows totaled 11 events; however, 51 spillway flows occurred between 1946 and 1986 (ASC/USCLD 1975, 1988). Of these 51 flows, the majority were on dams constructed after 1946. In the United

States, approximately 63 percent of large dams are less than 50 years old; yet fewer than 2 percent have received spillway flow. Large dams are built more hydraulically conservative than are small dams, and their spillways are designed to be seldom, if ever, used.

An examination of dams designed and constructed by the U.S. Department of Agriculture, Soil Conservation Service (SCS), predominantly small- and medium-sized dams, provides an even stronger argument. The largest number of dams was constructed during the 1964-1969 time period when over 5,000 dams were completed (SCS 1989a). The surge of SCS dam building is over, evidenced by the fact that only 334 dams have been constructed during the past 5 years. The total number of SCS dams placed in operation since 1954 is 22,785.

SCS spillway erosion problems were first documented in 1957; however, significant numbers of flows did not occur until late 1960s and 1970s (Ralston and Brevard 1988). The peak of dam construction occurred in 1964, but the first spillway flows for most sites did not transpire until 20 years later. Less than 5 percent of all SCS dams have experienced flows. It is probable that larger numbers of SCS dams will receive spillway flows. These statistics emphasize the importance of understanding the erosion process and using this knowledge to establish safety review, remediation, new design and redesign, and maintenance policies.

Purpose of an Emergency Spillway

An emergency spillway conveys flood flows that exceed the designed storage space safely past a dam. Several types of emergency spillway designs are currently used and generally classified according to their most prominent feature including: free overfall (straight drop), ogee (overflow), side channel, open channel (trough or chute), conduit, tunnel, drop inlet (shaft or morning glory), baffled apron drop, culvert, and siphon (Golze 1977). Emergency spillways, sometimes called auxiliary spillways, may also be classified as controlled or uncontrolled, depending on whether they are gated or ungated.

Open channel spillways, the focus of this study, are used with earth-fill dams more often than any other spillway type. Because 83 percent of the dams currently in operation are earth dams, it follows that a high number of open channel spillways are also operating.

Channel profile designs have an upstream entrance channel, a control structure, and a downstream exit channel. Control structures are generally placed in line with or upstream from the dam centerline (Figure 1). Downstream from the control, the exit channel is constructed at minimum grade until it "daylights" along the valley

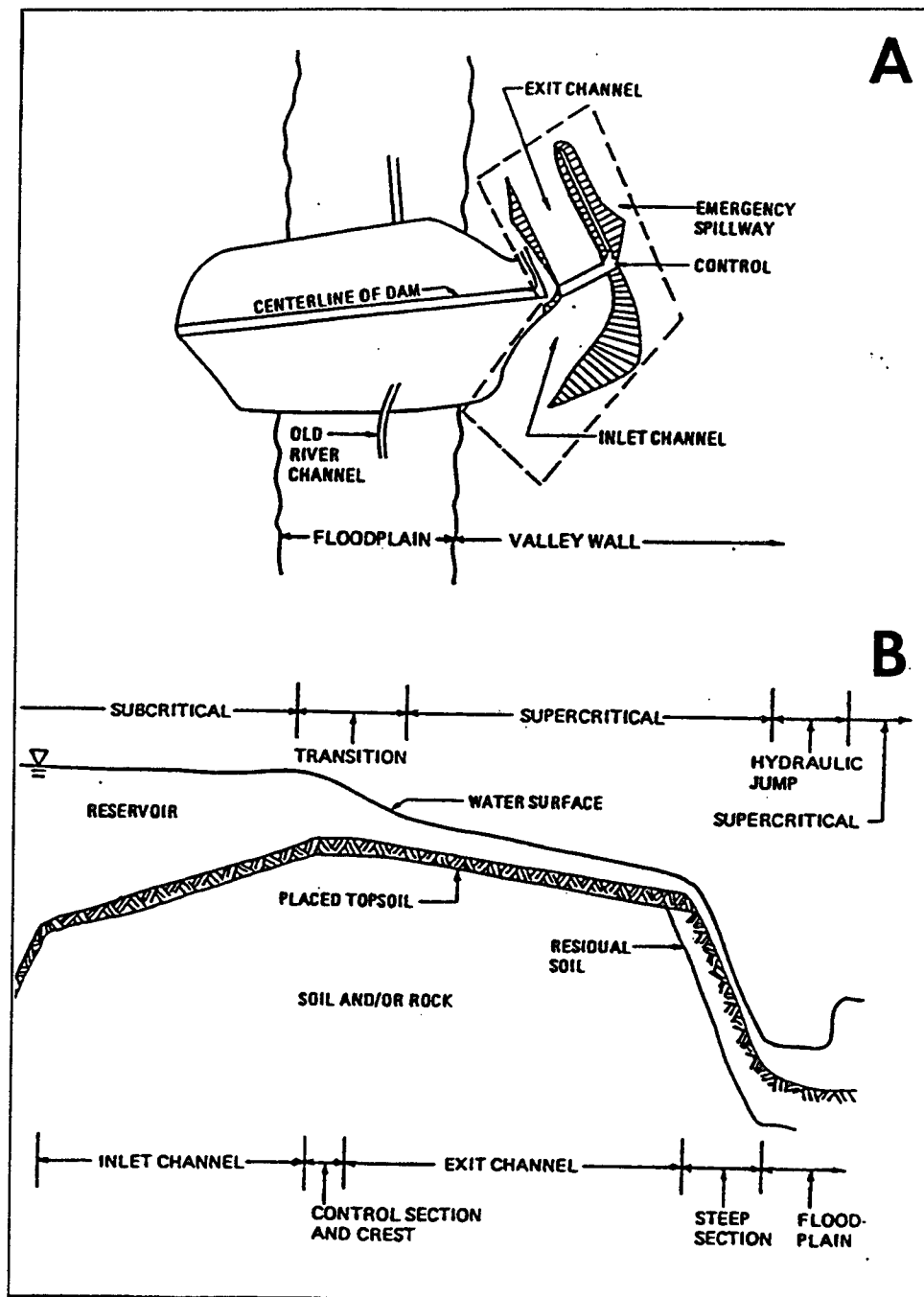


Figure 1. Plan view (A) and cross section (B) of a typical emergency spillway channel

wall. To minimize excavation, the channel is stopped at this location; the alternative would be to grade the channel a long distance along the valley wall and down into the floodplain. Depending on dam height and valley wall geometry, there is typically some drop-off or steeper gradient at the downstream end of the exit channel which grades to the floodplain elevation.

Adequate hydraulic capacity is a paramount criterion for emergency spillways of earth-fill and rock-fill dams which would potentially be destroyed if overtopped. Wide spillways are frequently constructed to meet this hydraulic capacity and to maintain shallow flow depths. This design concept calls for extensive spillway channel excavation, which comprises a significant amount of the overall construction cost.

Channel design relies on an assessment of flow risk versus capitalization cost. Emergency spillways are infrequently used with inconsequential erosion damage expected during operation (USACE 1965). However, there is an assumption in this philosophy that expected erosion will be minor and repairable. Recent findings show that numerous erosion estimates were too low and that excessive erosion occurred with flows below the maximum design flow (Cameron et al. 1986, 1988).

Previous Spillway Erosion Studies

The American Society of Civil Engineers and the United States Committee on Large Dams document spillway erosion by summarizing large dam failures and incidents dating to the late 1800's for United States dams (ASCE/USCLD 1975, 1988). Where possible, factors such as erosion involving only concrete, flow damaging only the controlling gates, or dam overtopping by excessive discharge are listed. However, a formidable number of incidents involve erosion of soil and rock. See Cato (1991) for a discussion of historical data.

The Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program spillway erosion study began in 1984 as a result of substantial spillway erosion at the U.S. Army Corps of Engineers' (CE) Grapevine Dam, TX, in 1981, and the CE-Saylorville Dam, IA, in 1984 (Cameron et al. 1986, 1988). Flow magnitudes represented small Probable Maximum Flood (PMF) percentages, but large rock volumes were eroded. More importantly, it was felt that larger flows would have produced spillway breaches.

The REMR study consisted of a reconnaissance stage assessing the problem magnitude and a research stage addressing specific issues. The reconnaissance study, performed by a multidisciplinary team based out of the U.S. Army Engineer Waterways Experiment Station in Vicksburg, MS, entailed contacting every CE Division to identify historic spillway flows. Efforts were made to visit each site, evaluate geologic materials in the spillway channel, and write up an event case history. Further research resulted in the following conclusions (Cameron et al. 1988):

- a. Structural and stratigraphic discontinuities play a major role in the erosion of rock by changing the erosion resistance of the bed material and forming channel gradient changes.

- b. It is possible to rank erosion at sites by comparing volumes of material removed.
- c. Headward knickpoint migration can be exacerbated by negative pressures pulling the turbulent forces of the nappe toward the natural materials in the headcut.

The SCS Emergency Spillway Flow Study Task Group (ESFSTG) evaluated the performance of more than 75 spillway flows to refine design criteria and guide repair of eroded sites.¹ Erosion severity varies from no damage to one complete breach. Observations show that most eroded material consists of placed soil on the exit channel floor and residual soil on the natural hillslope. However, the SCS is still trying to define erodible versus non-erodible rock.

Involvement with CE and SCS spillway studies led Cato (1991) to probe material performance case histories. Geometric and hydraulic effects on erosion processes were analyzed by statistically comparing erosion damage to geometric and hydraulic variables for 16 sites; portions of this work are summarized in Cameron et al. (1988). The analysis resulted in a method to classify erosion as dominantly downcutting, transition or backcutting. Conclusions reached were as follows:

- a. Generally, there is only minor statistical significance among the attempted correlations.
- b. The R-squared values for polynomial regression analyses were higher than those for linear regression analyses.
- c. Although the highest single R-squared value (0.79) occurred for the comparison of volumetric erosion ranking versus steep section length for the SCS dams, the overall R-squared values for the combined SCS-CE database were higher.
- d. The R-squared values for attempted correlations involving the geometric parameters were somewhat higher than those involving the hydraulic parameters including hydraulic attack.

The geologic and hydraulic significance of the regression analyses can be summarized as follows:

- a. Absence of overall significant statistical correlation among the sites in the database may be ascribed to variable geological conditions, particularly the nature of structural or lithologic discontinuities.

¹ Personal Communication, D.C. Ralston, 1989, National Design Engineer (retired), Engineering Division, Soil Conservation Service, U.S. Department of Agriculture, Washington, D.C.

- b. Regression analyses indicate that the effect of hydraulic parameters (water depth and velocity) play a minor role in predicting the nature and extent of erosion of rock-lined spillway channels, although these parameters should be important for predicting erosion in noncohesive soils and sediments.
- c. Higher R-squared values related to geometric parameters indicate that a knickpoint along the longitudinal profile of a spillway channel is important in initiating erosion and controlling the degree of erosion that will occur.

This initial study guided succeeding analyses to consider all three general variables (geometry, hydraulics, and geology). It was found that site geometry is a more critical factor in controlling the initiation of erosion than flow hydraulics and that site geology appears to serve as the dominant erosion control factor.

A follow-up statistical analysis incorporated geologic variables and a more detailed database (Cato 1991). Improvements over the previous comparison included the following:

- a. The database included only SCS dams in an attempt to consider dams of similar size and hydraulic conditions.
- b. Each channel was divided into segments of similar gradients; then, only damages from that segment were compared to hydraulic, geometric, and geologic variables.
- c. Performance of soil and rock materials were compared separately using linear and multiple linear regression techniques along with graphical displays of all comparisons.
- d. Comparisons of variables to the following measures of erosion:
 - (1) Damage classification.
 - (2) Area eroded in channel.
 - (3) Total volume of soil and rock eroded in channel (and unit volume).
 - (4) Volume of soil eroded in channel (and unit volume).
 - (5) Volume of rock and transition material eroded (and unit volume).
 - (6) Gully morphology (knickpoint shape and depth and hydraulic radius).

Rock mass classification systems, such as those by Kirsten (1988), Barton (1988), and Bieniawski (1988) developed for ripping and tunneling, had poor correlations. Rock Quality Designation (RQD), reported by Woodward (1985) to be a good indicator of erodibility, proved an ineffective indicator for the sites

analyzed in this study. The more descriptive system, the Unified Rock Classification System (URCS), and comparison of its components have merit.

Overall, the linear correlations are low, trends are not strong, and some apparent correlations, such as Standard Penetration Test (SPT) blow counts, are not valid because of sparse data. Multiple linear correlations also show low correlation coefficients, generally below 0.50, and show only moderate increases over linear coefficients. Observations at numerous sites attesting to geologic control cannot be ignored; therefore, statistical approaches with this amount or type of data are not adequate to show geologic effects.

2 Analysis and Prediction of Spillway Erosion

Classification of Erosion Damage

Investigated spillways came from two sources, the CE and SCS. SCS sites were generally more completely documented and were more similar in their size and characteristics than CE sites. The CE sites provide good geologic and hydraulic variation and represent larger structures.

Erosion classification enabled damage comparisons between sites. This was performed by developing an emergency spillway incident classification and classifying each channel segment. Erosion can be classified in many ways, including:

- a.* Erosion effect on dam operation.
- b.* Erosion process.
- c.* Volume of material eroded.
- d.* Area of exit channel scoured.
- e.* Repair cost.

The incident classification developed in this study is based upon the following hierarchy:

- a.* Damage to spillway structure whether it be a breach, severe erosion, or only minor erosion.
- b.* Type of materials eroded whether it is placed topsoil or *in situ* rock or soil.

The erosion damage classification system developed by Cato (1991) is presented in the following:

- a. *Failure Type 2 (F2)*. Applies only if breach occurs. A major failure of an operating dam which involved complete abandonment of the dam.
- b. *Failure Type 1 (F1)*. Applies only if breach occurs. A failure of an operating dam which at the time may have been severe, but was of a nature and extent that permitted successful damage repair and continued operation. For example, an F1 failure could be produced by breach of spillway control section with uncontrolled release of reservoir waters.
- c. *Erosion Type 2 (E2)*. Erosion in excavated spillway channel and/or erosion at the downstream end of the excavated spillway that consisted of a great deal of natural *in situ* material in addition to placed topsoil. This type of erosion would cause severe damage to the spillway, but would not cause breach and release of reservoir waters. This type of erosion involves the same processes as in E1, but damage severity, and hence cost to repair, is greater.
- d. *Erosion Type 1 (E1)*. Erosion in excavated spillway channel and/or erosion at the downstream end of the excavated spillway that consisted primarily of the removal of soil and possibly some rock, material. This type of erosion would cause minor to moderate damage to the spillway exit channel or downstream reaches. This type of erosion would also include headward migration of gullies if the erosion is removing natural *in situ* rock or a residual soil and/or formation of scour holes where the spillway waters enter the floodplain.
- e. *Scour Type 1 (S1)*. Erosion in the excavated spillway that consists of removal of only topsoil. A technical breach, one in which erosion progresses through the control section, could be S1 if the depth of erosion does not involve *in situ* rock or residual soil.
- f. *Vegetation Removal (VR)*. Removal of some vegetation and only minor amounts of soil.
- g. *No Damage (ND)*. Emergency spillway suffered no soil erosion or vegetation removal.

The observed damages range from almost no erosion in any channel segments at site SCS AR - West Fork Point Remove 10 (SCS AR-WFPR-10); to severe erosion and significant repair costs at CE-Grapevine, TX, CE-Saylorville, IA, and SCS AR-WFPR-3; and finally a complete breach at SCS MS-BC-53. See Cato (1991) for a detailed discussion of the erosion damage and characteristics of the spillway channels evaluated to develop his classification system.

Based on the performance of various geologic units subjected to erosive stresses, the spillway incident classification was used to define a spillway erosion potential classification system. This system separates material into four classes:

- AAAA = Erosion-resistant rock
 AAA = Moderately erosion-resistant rock
 AA = Moderately erodible material
 A = Erodible soil

Stable conditions for each class are given in the form of slope, maximum flow velocity, expected erosion, and effect of anomaly on erosion (Figure 2). Expected erosion is based upon the incident classification established by Cato (1991). Class A is for nonvegetated soil because vegetation can offer protection up to 7 ft/sec. Anomalies refer to breaks in surface cover produced by roads or lineations in the vegetation and pilot channels, knickpoints, or other abrupt slope changes.

CHANNEL STABILITY	EROSION RISK CLASS			
	AAAA	AAA	AA	A
Slope (percent)	30-45	15-30	4-15	< 4
Flow Velocity (ft/sec)	10-15	7-10	4-7	< 4
Anomaly Effect	Minor	Moderate	Major	Severe

Figure 2. Relationship between rock-erosion classification and geometric and hydraulic characteristics of the spillway channel. For example, a rock classified as an AAAA is predicted to be able to withstand flows in a channel of from 10 to 15 ft/sec

Spillway Channel Erosion Equation

The previous work to assess the erosion potential of geologic materials, both descriptively or in an application, inadequately assesses erodibility behavior. Multidisciplinary studies of spillway channel erosion have determined that three major factors control erosion (Cameron et al. 1986, 1988; SCS 1987b). These factors can be expressed qualitatively as:

$$E = f(C, H, G) \quad (1)$$

where

- E = Erosion
 C = Channel geometry
 H = Hydraulics
 G = Geology

¹ A table of factors for converting non-SI units of measurement to SI units can be found on p. vii.

The precedence and usefulness of a qualitative equation come from kindred approaches investigating soil formation and soil erosion. In 1941, Jenny (1941) proposed the soil forming factor equation, today popularly known as the "CLORPT" formula:

$$SF = f(CL, O, R, P, T) \quad (2)$$

where

SF = Soil formation
 CL = Climate
 O = Organics
 R = Relief
 P = Parent material

Jenny felt that quantification of these factors was impossible, but explicit identification of these factors in an equation made more detailed studies possible. The Universal Soil Loss Equation also exemplifies usefulness of this approach (Smith and Wischmeier 1962). In this case, soil loss is a function of:

$$SL = f(LS, P, C, R, K) \quad (3)$$

where

SL = Soil loss
 LS = Length slope
 P = Conservation practices
 C = Cropping or vegetation type
 R = Rainfall
 K = Material type

Both of these equations list all factors affecting the stated process as a guide for other workers, but are not a "cookbook approach" because resulting accuracy depends totally upon the user's judgment.

This concept of a qualitative factorial equation to predict emergency spillway erosion is the basis of the erosion prediction technique developed in this study. Equation 1, the spillway channel erosion equation addresses, channel geometry (C), hydrology/hydraulics (H), and geology (G).

Channel geometry (C)

Channel geometry, C, can be used as a first approximation in erosion prediction. An important design factor is the vertical drop that takes place along the spillway channel length; the drop represents potential energy to erode. Other geometric factors include:

- a. Channel width.
- b. Excavated channel length.
- c. Excavated channel gradient.
- d. Length of steep section.
- e. Steep section gradient.
- f. Channel form anomalies, such as pilot channels, knickpoints, and flow concentrators

Channel geometry factors greatly influence flow regime and erosion processes acting in the spillway channel (Chow 1959). Field inspections of emergency spillways that experienced erosion during flow events revealed that the initiation of erosion was often associated with a geomorphic anomaly. For example, the existence of a local road and fill within the spillway channel at CE Grapevine Lake acted like an overtopping dam and concentrated erosive energy at the downstream toe of the fill. This resulted in the development of deep channel "gully" erosion. Other observed anomalies that concentrate flow and therefore establish the point of initial erosion include pilot channels, trees and clump grasses, and abrupt changes in channel gradient, such as at the interface between the channel and the original floodplain.

Hydrology/hydraulics (H)

Channel geometry combined with site hydrology establish hydraulic forces operating in the spillway channel. Hydraulic factors, H, include:

- a. Instantaneous peak flow.
- b. Cumulative flow.
- c. Flow duration.
- d. Flow depth.
- e. Flow velocity.

The hydrology of the drainage basin above the spillway combined with the operational procedures at the particular structure are the controlling factors on the flow conditions in the spillway. Postflow field inspections of eroded spillway channels revealed that once erosion was initiated at some geometric anomaly, the primary erosion mechanism was either boundary shear, as at CE Lewisville, or back cutting of knickpoints, as at CE Grapevine and CE Saylorville.

The controlling hydraulic factor in boundary shear erosion appears to be flow velocity, while in knickpoint erosion the controlling factor is a combination of geometry and flow depth. May (1988) showed in fixed bed experiments on knickpoint hydromechanics that the greatest knickpoint migration rates may not correspond to highest velocity or discharge. May identified two significant conditions: (a) the relative depth of flow compared to the height of the fall (Figure 3) and (b) the degree of hydraulic venting below the nappe of the overfall (Figure 4). In the first condition, as flow depth increased compared to the height of the fall, the influence of the geometric anomaly decreased until it eventually became a part of the channel roughness. Unvented knickpoints accelerate headcutting by orders of magnitude greater than vented knickpoints. Analyses of flow events determined that unvented conditions commonly occur in excavated spillway channels during conditions of below design peak flows. Robinson (1988, 1989) showed that low tailwater depths allow greater stress impacts on the knickpoint face and in the plunge pool than do high tailwater levels and that the rate of knickpoint migration can be slowed tremendously by increasing water depth and submerging the overfall.

Geology (G)

Geologic factors, G, are the least understood of the three major variables; are independent of site hydraulics or channel geometry; often control spillway design; and, most significantly, govern all erosion processes. For example, a spillway excavated into massive unfractured granite can be much narrower and can be excavated at a steeper gradient than one with a loess foundation because of the greater erosion resistance of the granite. However, predicting erosion resistance of natural materials is seldom this clear-cut because a great number of geologic variables create immense numbers of situations possible.

To provide analytical structure, a geologic erosion equation is proposed to concisely express critical geologic variables influencing erosion. The equation

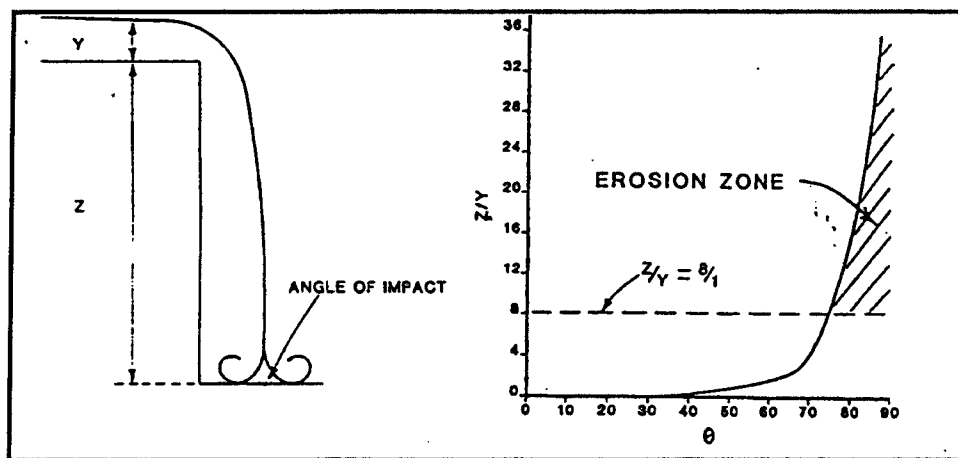


Figure 3. Relationship between flow depth and fall height (after May 1988)

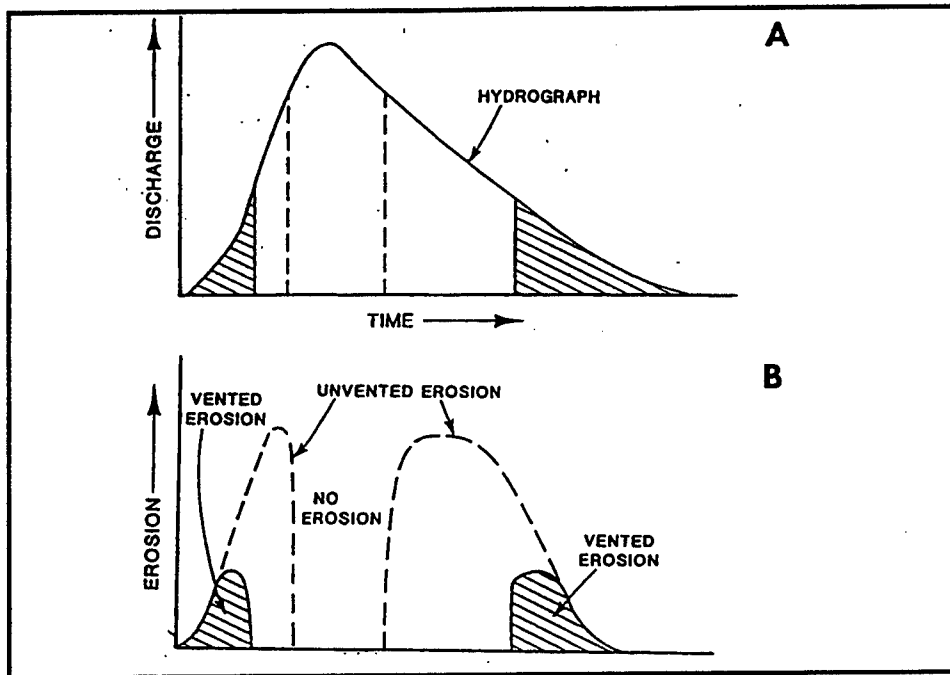


Figure 4. Flood hydrograph (A) of a flow event that reaches peak design discharge showing erosive flows during vented (cross-hatched), unvented, and peak flows. Erosion hydrograph (B) showing the conditions when vented (hatched) and unvented erosion occurs. Note the significant increase in erosion during unvented conditions (after May 1988)

reads:

$$GR = f(L, SP, G, ST, MP) \quad (4)$$

where

- GR = Geologic resistance to hydraulic erosion
- L = Lithology
- SP = Rock substance properties
- G = Genesis of the material
- ST = Structure and tectonic history
- MP = Rock mass properties

Some lithologies unceasingly erode while others have never been observed to erode within a human time frame. Rock substance properties define whether material behaves as soil or rock, that is, whether it erodes in a grain-by-grain fashion or detaches along discontinuities as blocks. Defining soil versus rock with accepted definitions, such as strength, is not justifiable because strength alone does not appear to control erodibility. Genesis of the material determines lateral continuity, bedding thickness, and types of interbeds. Structural and tectonic

history determine rock unit orientation. Unit orientation can channelize and shift erosion toward the dam if units strike parallel to flow or can significantly reduce erosion if units dip upstream into the flow direction. Rock discontinuities, such as fractures, function as detachment surfaces that define rock blocks. The following sections describe the role of each of the geologic factors and define an erodibility classification for each.

Lithology. Different erosion processes observed for various rock types indicate the first and most significant erosion criterion should be lithology. Lithology is the basic classification of natural material for a geologist and relates to material genesis. The three general lithologic types are igneous, sedimentary, and metamorphic. Spillway flows have been documented on two of the three lithologic types, but by far the greatest frequency of flows has occurred on sedimentary rock. Observed rock types include:

- a. Extrusive igneous.
- b. Intrusive igneous.
- c. Clastic sedimentary (sandstone and shale).
- d. Organic sedimentary (limestone).

Clastic sedimentary rocks make up most observed sites; this is expected because clastic sedimentary rocks comprise approximately 80 percent of the U.S. surface area. Metamorphic rocks and chemical sedimentary rocks were not evaluated.

Igneous and metamorphic rocks have a wide range in their resistance to erosion, but not as great as that observed for sedimentary rocks. Relative to sedimentary rocks, igneous and metamorphic rocks tend to have higher strengths and densities and display competent mass properties. Igneous and metamorphic rocks display block-by-block detachment processes rather than single-grain erosion processes. No examples exist of severe threatening spillway erosion in these types of lithologies.

Sedimentary rocks have an extensive range of physical properties, and most examples of spillway erosion are from clastic sedimentary rocks. This is caused by the fact that most examples of spillway erosion came from structures built by the SCS and their projects are predominantly located on sedimentary bedrock.

Lithologies, discharge, and effect of lithology on erosion are given in Cato (1991). Selected case histories for various lithologies are presented below:

- a. *Sandstone.* A resistant sandstone unit provided ample resistance to the 1984 flow at CE-Saylorville, IA. The ogee weir control structure is founded on this unit as well as is the exit channel. A drop-off occurs, however,

downstream of the exit channel along with channel narrowing and flow concentration. Shales with some interbedded sandstones and siltstones comprise the stratigraphy of the steep section. The flow produced a series of overfalls (stairsteps) which migrated moderate amounts upstream. The sandstone unit itself, comprising the exit channel floor, was quite resistant. Dislodgment of large sandstone blocks did occur because the shale foundation for each block could not resist the flow attack.

- b. *Siltstone*. The CE-Grapevine, TX, spillway erosion in 1981 was the biggest factor persuading the USACE to establish its rock erosion study (Cameron et al. 1986). Severe gulying and downcutting of the excavated channel threatened site integrity and were produced by a 9,000 cfs flow. Initially, it was thought that a resistant sandstone unit would provide adequate erosion resistance to prevent downcutting and headward gully migration. However, the sandstone unit, part of an old fluvial and deltaic sequence, was laterally discontinuous and underlain by highly erosive, interbedded siltstones, shales, and sandstones. The rock substance properties of the siltstones, low plasticity indices, indicated the material was erodible.
- c. *Shale*. SCS WV-SF-17 shows how a shale can be very resistant. The exit channel discharges onto a 41-percent slope which drops 70 to 80 ft down to the floodplain. Flow removed waste rock placed on the steep slope during construction and uncovered a shale bedding plane. Blocks of shale were removed by mass wasting processes as the toe of the slope was undercut; however, very little shale was removed during this extreme attack. CE-Lewisville, TX, experienced spillway flow at the same time as the Grapevine flow (Cameron et al. 1986). In this case, attack only removed a surficial veneer of weathered and desiccated shale. Unweathered Eagleford shale was quite resistant to erosion.
- d. *Cohesive soil*. A good example of soil material resistance is a January 1989 spillway flow in Kentucky at an SCS spillway, KY-UT-8. A gradient change at the downstream end of the excavated emergency spillway channel from 2.5 to 20 percent produced eroding velocities. Colluvium blanketed dipping sandstones and shales in the area where erosion was concentrated. The colluvium, classified as a soil GM by the Unified Soil Classification System, was resistant to erosion and performed almost as well as the rock. The colluvium that did erode did not do so in a grain-by-grain detachment of gravel, sand, and silt particles. It detached along soil mass discontinuities producing blocks of colluvial material, some as much as 1 ft in diameter.
- e. *Granular soil*. Mississippi Black Creek, MS-BC-53, was a soil spillway that breached in 1983 (Temple 1989). The highly erosive loess, sand, and gravel offered very little erosion resistance to the flow once a gully began migrating headward. The lithology of this site indicated that it was highly susceptible to erosion. The sediment was very poorly cemented and had a very low density. It is thought that both grain-by-grain detachment and

block detachment processes operated during this flow event. The loess detached along soil mass discontinuities and because of its low density was able to be transported downstream as discrete soil particles.

The erosion classification for lithology (Figure 5) is a guide to expected performance range and is not used to place material into an erosion class; this equips the user with an expected performance range. Determination of subsurface lithology requires more interpretation and hence more subjectivity than the other categories which can be directly measured. Although metamorphic rocks were not analyzed, studies of their physical rock properties and direct observations indicate these rocks should be moderately resistant to erosion

Rock substance properties. Rock substance properties involve properties of mineral grains and bonds between grains. These include density, strength, hardness, permeability, weathering, grain size, and grain shape. Observations indicate density, strength, and weathering play significant roles in the erosion process. These properties play a significant role in erosion of soils and very weak rock because these materials detach in a grain-by-grain process. With competent rock materials, the rock substance properties of cementation, strength, and density are better developed, and the mass properties become the controlling factors.

Greater amounts of weathering increase erodibility; weathering also changes density and strength. It is believed that a discussion of density and strength effects on erosion will indirectly address effects of weathering. Density influences entrainment by creating a particle too heavy to move. Soil aggregates with densities in the range of 90 to 110 pcf are more easily transported than gneissic blocks of the same size with densities greater than 150 pcf. Strength is a significant factor at low material strengths, generally in the 100 to 2,000 psi range. In this range, material strength between grains or soil aggregates cannot resist flow attack. Above this range, the material substance properties create significant resistance, and the mass properties become the controlling factor.

LITHOLOGY	EROSION POTENTIAL CLASS			
	AAAA	AAA	AA	A
Sandstone	XXXXXXXXXXXXXXXXXXXXXXXXXXXX			
Shale & Siltstone	XXXXXXXXXXXXXXXXXX			
Limestone	XXXXXXX			
Granular Soil (Low PI)				XXXXXXX
Cohesive Soil (High PI)			XXXXXXXXXX	
Intrusive Igneous	XXXXXXX			
Extrusive Igneous	XXXXXXXXXXXXXXXXXXXX			
Massive Metamorphic	XXXXXXXXXXXX			
Foliated Metamorphic	XXXXXXXXXXXXXXXX			

Figure 5. Rock erosion potential class based on lithology

The erosion classification for rock substance is composed of both rock density and rock strength (Figure 6). These properties are related to the URCS and can be determined from this system.

Genesis. Processes that form or deposit geologic units determine the three-dimensional extent of each rock and soil bed. These processes are highly complex and produce materials which are anisotropic, heterogeneous, and discontinuous. The physical rock properties frequently change drastically along the length and/or width of the spillway channel. Knowledge of formational processes yields an understanding of material continuity and its properties. For example, a sandstone which formed from a river sand would be expected to be highly discontinuous, whereas a marine shale should be more continuous.

The environment of formation establishes first-order discontinuities in a rock material; changes in this material after it has formed into rock, such as folding and fracturing, are second-order discontinuities. The second-order discontinuities are produced by the structural and tectonic history. An example of a first-order discontinuity would be vertical bedding changes in a stratigraphic section. It is common to find a description which might read, "interbedded sandstone and siltstone." This just implies changes in the energy available at the time of deposition. Practically, one should expect sandstones in this type of interbedded sequence to also vary more along the length and/or width of the spillway than the siltstones because sand, which requires more energy to transport, tends to follow pre-existing channels. Higher depositional energy will yield more variation in rock properties, and vertical and lateral variation in these units will have a direct effect on the erosion process. Selected case histories that demonstrate the influence of genesis on spillway channel erosion are presented in the following:

- a. SCS TX-Big Sandy-10 has a spillway in Pennsylvanian clastic sediments ranging from thinly bedded sandstone near the crest, to thick sandstone units over the middle and lower lengths, to shale at the bottom of this approximately 15-percent grade. Spillway flow removed all vegetation and created a scour hole where the 15-percent grade exited onto a level floodplain. The scour hole formed in easily erodible weathered shale. Erosion was resisted by two factors: the shale became more resistant further into the slope, and the thick sandstone units provided a resistant cantilever which protected the underlying shale from additional undermining. If the thinly bedded sandstone units had directly overlain the shale, it is probable that more headcutting would have occurred, with a resulting sloped or strair-stepped morphology rather than an overfall.

SUBSTANCE	EROSION POTENTIAL CLASS			
	AAAA	AAA	AA	A
Density (pcf)	> 140	140-125	125-116	< 116
Uniaxial Strength (psi)	> 6000	6000-2000	2000-150	< 150

Figure 6. Rock erosion potential class based on rock substance properties

- b. SCS WV-SF-10 exemplifies how lateral changes in material resistance affect the erosion process. Genesis indicates that marine shales comprising the majority of the bulk spillway length should be very continuous. The tectonic history indicates stresses that caused the rock to be tilted and to dip upstream and under the dam. The environment of formation in a much more recent sense, the creation of the valley and alluvial deposits, suggests that alluvial terrace material exists near the floodplain. At the downstream end of the exit channel, fluvial terrace material was encountered. The deepest gullies produced by the 1986 event occurred in the terrace material. Erosion of the alluvial material is not surprising, but the removal of this material created a knickpoint in the spillway channel and allowed increased attack on the shale.

The erosion classification based on genesis includes two components, vertical consistency and lateral consistency (Figure 7). Vertical consistency addresses the first-order discontinuities, thickness of each bed within each unit exposed in the channel. As bed thickness increases, the rock unit becomes more massive and generally stronger, resulting in increased resistance and lower erosion potential. Lateral consistency is a measure of the total number of different rock facies or subunits exposed along the strike of a sedimentary bed. This factor addresses the problem of uniformity to erosion along the entire exposure of a unit. A uniform unit is expected to erode in such a manner that secondary knickpoints and other anomalies in the channel geometry will not develop and accelerate erosion.

GENESIS	EROSION POTENTIAL CLASS			
	AAAA	AAA	AA	A
Vertical Consistency (ft)	> 6	6-2	2-.25	< .25
Lateral Consistency (#)	1	2	> 2	> 2

Figure 7. Rock erosion potential class based on rock genesis and environment of formation that produce the first-order discontinuities

Structural and tectonic history. The structural and tectonic history of an area controls the rock body orientation and the amount of fracturing in the rock mass. Orientation of the rock units can be horizontal or dipping. The most favorable orientations are horizontal or those that dip upstream toward the flow; units that dip downstream with the flow direction accentuate mass failures at the downstream end of the excavated channel; and units that trend across the spillway channel and strike parallel to subparallel to the channel centerline cause highly complex erosion patterns resulting from channelization of the flow along bedding units which accentuates erosion. In cases where the spillway channel changes direction as it drains toward the valley, complex erosion patterns may also develop. For example, channel erosion may actually shift toward the main embankment if the channel is aligned parallel to the strike of a set of beds that dip under the dam. Erosion of the main embankment by this process has not been observed; however, minor erosion of the training dikes has been observed when

these conditions exist. Selected examples of the influence of tectonics on spillway erosion follow:

- a. SCS WV-SF-10 also demonstrates the effect of unit dip on erosion. The rock dips under the dam and strikes almost parallel to the centerline of the spillway channel. As incisement through the topsoil progressed into the underlying shale, flow on the sloping bedding plane shifted erosion toward the dam.
- b. At CE Wister, OK, the rock dips downstream and in the direction of flow. This spillway channel has sustained two flow events without severe damage (Cameron et al. 1986). The block-by-block detachment has left a very jagged surface, but the rock mass is competent enough to withstand several more flows of these magnitudes. The rock units in this case dip downstream at a steeper angle than the channel slope, which requires the hydraulic erosive forces to fracture the rock before erosion can occur.

Classification of erosion resistance related to tectonics is shown in Figure 8. This factor includes only the relationship between the direction of spillway flow and the orientation of the bedrock units.

TECTONICS	EROSION POTENTIAL CLASS			
	AAAA	AAA	AA	A
Unit Orientation Related to Flow Direction	Flat	Dip Toward	Dip Parallel	Dip Away

Figure 8. Rock erosion potential class based on tectonic history of the rock that produces the second-order discontinuities

Rock mass properties. Rock mass properties are probably the most important of all in controlling erosion. Discontinuities such as fractures, joints, or bedding planes provide weaknesses along which detachment can take place. Postformational changes, second-order discontinuities, in the rock mass are generally termed rock mass properties. Another definition of rock mass properties is that they cannot be taken into the laboratory and measured because they are large-scale features, such as a fracture set or fold. Rock mass properties include bedding thickness, rock orientation, and rock fracturing and can be mapped in an exploration trench or during excavation of the channel.

A direct result of the tectonic stresses placed on the rock mass is jointing and fracturing in a rock body. These discontinuities are weaknesses in an otherwise nonerosive surface. Hydraulic forces make use of these planes of weakness to pluck, slide, and otherwise detach rock particles from the mass. Massive unfractured rock is considerably more erosion resistant than is broken or shattered rock. Structural discontinuities are not random, but are related to the structural history of the site.

Human-made discontinuities produced in an otherwise uniform surface or massive rock can contribute to the erosion of a spillway. For example, shale overlying the spillway at a dam in Arkansas had to be blasted to permit excavation; however, overblasting created fracturing in the spillway floor. Subsequent flow easily entrained the small loose shale particles created by the blast. Block size increased radially away from the blast zone, which in turn produced a more resistant surface. Greatest erosion at this site was at the center of the blast zone.

Clemence (1988), in wind tunnel experiments, investigated the influence of fracture spacing and bed thickness of channel floor rock units on the mechanisms of knickpoint retreat. Clemence's experiments determined that in addition to the traditional cantilever type failure, where the overlying competent bed fails upon removal of the erodible underlying bed, the caprock can be removed by boundary shear and uplift pressure (Figure 9). The eroded form of the caprock can range from a single cliff in a massive caprock to a series of stairsteps in a thinly bedded caprock that contains widely spaced fractures. In thinly bedded, close fractured, caprock units, slabs of caprock are removed by boundary shear developed by the flowing fluid or through uplift pressures that develop within a permeable underlying unit. Clemence's study indicates that knickpoint retreat rates can be reduced or controlled by binding the caprock together using rockbolts to form a thicker unit.

Rock mass properties are one of the most important components of the erosion classification system because their effect has been observed in all sites studied (Figure 10). The rock mass classification includes fracture spacing, particle diameter, fracture opening, and number of fracture sets. Fracture (joint) spacing along with bedding plane separations control rock particle size and shape. Thinly bedded, closely fractured units can be easily lifted from the floor of the channel and are carried out of the area by "sailing" in the flowing current. Particle diameter is calculated for each erosion class by the following formula:

$$D = (L_1 L_2 L_3)^{1/2} \quad (5)$$

where

- D = Average particle diameter
- L₁ = Length of longest dimension
- L₂ = Length of medium dimension
- L₃ = Length of shortest dimension

Fracture openness and cementation determine locking of particles against detachment. The number of fracture sets establishes particle size.

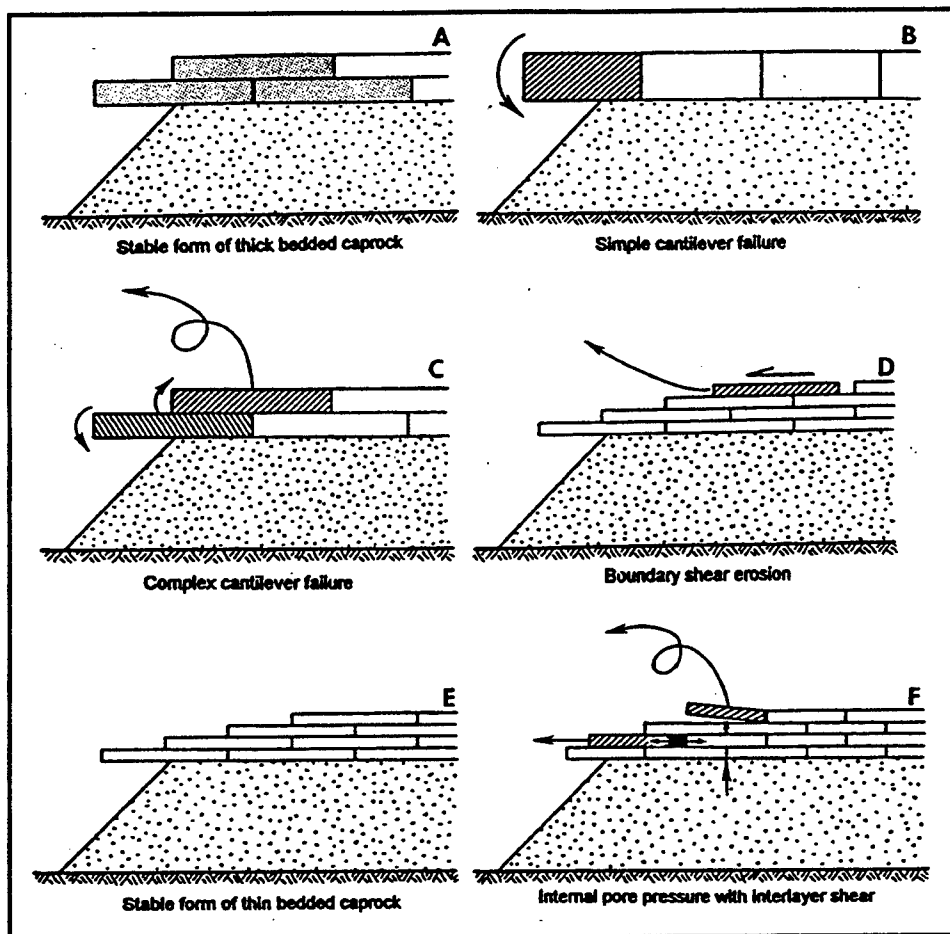


Figure 9. Schematic cross sections of model knickpoints investigated by Clemence (1988); (A) stable form for thick bedded caprock with offset fractures; (B) thick massive caprock failing by cantilever rotation as the underlying supporting layer is eroded; (C) cantilever failure mechanism of a thick bedded caprock with offset fractures; (D) erosion of thinly bedded caprock by boundary shear; (E) most stable form for thinly bedded caprock (note the similarity to A); (F) failure mechanism in thinly bedded, close fractured caprock by interlayer shear and internal pressure conditions (after Clemence 1988)

Predicting Rock Erosion in Spillway Channels

Documentation of spillway flow events at numerous SCS, CE, and private dams provides a database from which to develop empirical relationships regarding earth material performance under hydraulic stresses. The erosion performance of an emergency spillway channel was found to be related to an interaction between the channel geometry, flow hydraulics, and site geology. Channel geometry and hydraulics are interrelated through the basic laws of hydrology. Site geology is an independent factor that often control channel geometry. Therefore, any technique

ROCK MASS	EROSION POTENTIAL CLASS			
	AAAA	AAA	AA	A
Fracture Spacing (ft)	> 3	3.0-1.0	1.0-0.5	< 0.5
Particle Diameter (ft)	3-5	1-3	1-.5	< .5
Fracture Size/Opening (in)	< 1/8	1/8-1/2	> 1/2	open/clean
Fracture Sets (No.)	2	2-3	> 3	shattered

Figure 10. Rock erosion potential class based on rock mass properties

to predict emergency spillway channel erosion potential must incorporate and evaluate all three primary factors in channel erosion, $E = f(C, H, G)$. A proposed procedure to estimate emergency spillway channel erosion potential is given below:

- Determine the Erosion Risk Classification (Figure 11) for each segment of the channel based on the geometry and flow characteristics of the existing, proposed, or designed spillway channel. Incorporate any topographic anomalies, such as pilot channels, road fills, and gradient changes at the channel-valley boundary. Record the results on the Spillway Erosion Assessment Sheet (Figure 12).
- Evaluate all site investigation data, field surveys, and flow histories for the channel under consideration. Using the Erosion Potential Classification (Figure 13), determine the erosion potential class for each identifiable rock unit exposed or possibly exposed in the spillway channel for each of the factors in the geologic erosion equation (Lithology, Rock Substance Properties, Genesis, Tectonics, and Rock Mass Properties). Enter the erosion potential class for each bed and factor on the Spillway Erosion Assessment Sheet (Figure 12).

EROSION RISK	EROSION RISK CLASS			
	AAAA	AAA	AA	A
Slope (percent)	30-45	15-30	4-15	< 4
Flow Velocity (ft/sec)	10-15	7-10	4-7	< 4
Geometric Anomaly	Extreme	Major	Moderate	None
AAAA	Significant Erosion Risk			
AAA	High Erosion Risk			
AA	Moderate Erosion Risk			
A	Slight Erosion Risk			

Figure 11. Erosion risk classification based on slope, flow velocity, and geometric anomaly within the spillway channel

- c. Compare the Erosion RISK Classification with the Erosion POTENTIAL Classification for each unit exposed within the channel. In each case where the POTENTIAL of a unit is less than the RISK (more erodible), special engineering geologic attention and design consideration are required for the unit. If the RISK is less than the POTENTIAL (more erosion resistant), the unit can be considered to be stable under the proposed geometric and hydraulic conditions. It is important to recognize that this technique is empirical and that good engineering judgment will be required for each evaluation.

[illegible]

Figure 12. Spillway erosion assessment sheet used to compare erosion risk to erosion potential for each geologic and geometric section within the spillway channel

EROSION POTENTIAL	EROSION POTENTIAL CLASS			
	AAAA	AAA	AA	A
AAAA	Erosion Resistant Rock			
AAA	Moderately Erosion Resistant Rock			
AA	Moderately Erodible Material			
A	Erodible Soil			
LITHOLOGY				
Sandstone	XXXXXXXXXXXXXXXXXXXXXXX			
Shale & Siltstone	XXXXXXXXXXXXXXX			
Limestone	XXXXXXX			
Granular Soil (Low PI)				XXXXXX
Cohesive Soil (High PI)			XXXXXXX	
Intrusive Igneous	XXXXXXX			
Extrusive Igneous	XXXXXXXXXXXXXXXXXXXXXXX			
Massive Metamorphic	XXXXXXXXXXX			
Foliated Metamorphic	XXXXXXXXXXXXXXX			
SUBSTANCE				
Density (pcf)	> 140	140-125	125-116	< 116
Uniaxial Strength (psi)	> 6000	6000-2000	2000-150	< 150
GENESIS				
Vertical Consistency (ft)	> 6	6-2	2-.25	< .25
Lateral Consistency (#)	1	2	> 2	> 2
TECTONICS				
Unit Orientation Related to Flow Direction	Flat	Dip Toward	Dip Parallel	Dip Away
ROCK MASS				
Fracture Spacing (ft)	> 3	3.0-1.0	1.0-0.5	< 0.5
Particle Diameter (ft)	3-5	1-3	1-.5	< .5
Fracture Size/Opening (in)	< 1/8	1/8-1/2	> 1/2	open/clean
Fracture Sets (No.)	2	2-3	> 3	shattered

Figure 13. Erosion potential classification based on lithology, rock substance, material genesis, postformational discontinuities (tectonics), and rock mass properties

3 Repair and Remediation of Spillway Erosion

As discussed in the previous section, spillway channel erosion can be expressed as

$$E = f(C, H, G) \quad (1 \text{ bis})$$

where E = erosion, C = channel geometry, H = hydraulics and G = geology. This same relationship can be used as a basis for the repair and remediation of erosion. Each of the primary factors is addressed individually and then summed to obtain the ultimate design concept for spillway repair.

Channel Geometry

Field observations (Cameron et al. 1986, 1988; Cato 1991) and fixed and movable-bed laboratory investigations (May 1988) have shown that geometric anomalies in the channel section frequently control the initiation and character of channel erosion. A significant factor in limiting the initiation and degree of erosion during spillway flows is the uniformity of the channel form.

Spillway channel maintenance should be a standard practice for all structures. Spillways should be maintained for their intended purpose: to carry flood waters in an emergency. Spillways should be kept clear of large vegetation and maintained with a thick grass mat where possible. Secondary uses, such as four-wheeler mud contests, picnic areas, roadways, and recreation areas, should be kept out of the channel. Once the channel has been cleared of any obstructions, it should be inspected for any geometric features that would concentrate flows, such as pilot channels, or abrupt changes in slope or channel width. These areas should be evaluated and redesigned such that their impact on the hydraulics of the channel are minimized. In cases where it is not economically or physically possible to remove or significantly modify these features, appropriate structural designs may be needed.

Knickpoints and other abrupt changes in channel slope require special treatment. Laboratory studies by May (1988) determined that the critical period of

knickpoint erosion occurs during the rise and fall of the hydrograph at discharges that are significantly below the design peak flow (Figure 4). These features should be treated similar to hydraulic drop structures and designed with some mechanism to vent the nappe or as a hydraulic flow structure, such as an ogee weir and stilling basin, designed to pass the water without erosion. The selection of the appropriate design concept depends upon the geologic characteristics at the site. Similar consideration is necessary in areas where the channel narrows or abruptly changes direction.

Hydrologic and Hydraulic Conditions

The lake manager has limited opportunity to modify the hydrology of the upstream drainage basin unless there are existing flood management structures in the area. If so, it may be possible to implement a flood management program that allows the system manager the flexibility to control the amount of water discharged through an emergency spillway channel such that minimal erosion flows can be generated. In most cases, it is unlikely that this management tool will be available; however, any multidam system should be evaluated for this possibility.

It is more likely that the operator of a dam may be able to influence the amount of flow in their own spillway by controlling the amount of discharge through the gates. For example, a gated emergency spillway may be opened only after sufficient head has built up behind the gates to minimize the erosive rising and falling stages of the hydrograph.

Geologic Conditions

Channel geometry and hydraulic conditions establish the potential for erosion and generally identify the point of initiation and character of erosion. The geologic characteristics of the site, however, control the rate and mechanism of erosion. Of the geologic factors identified in the geologic erosion equation, $GR = f(L, SP, G, ST, MP)$, genesis of the material (G), and structure and tectonic history (ST) cannot be easily modified without changing the location or orientation of the spillway channel. The other factors, rock substance properties (SP) and rock mass properties (RM), however, can be modified to produce a more suited spillway material.

Field observations indicate that erosion is frequently concentrated at the interface between concrete structures and the natural ground. This interface is similar to an abrupt geologic boundary established during the formation of the rock body. It is recommended that a cutoff wall be incorporated into the terminal end of all concrete structures to prevent undercutting of the foundation of the structure (Figure 14).

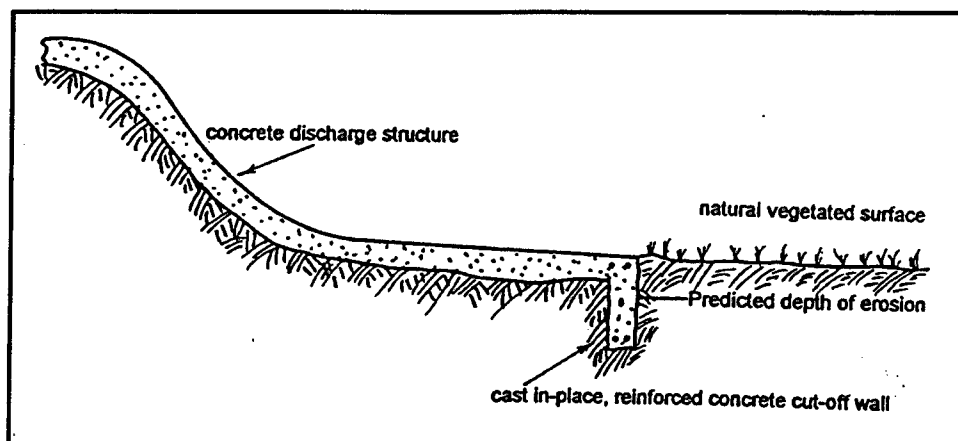


Figure 14. Conceptual section of a cutoff wall at the toe of a concrete discharge structure to resist undercutting

Low-strength granular soils and weakly cemented sedimentary rock units can be improved through soil-cement treatments. Soil-cement treatment of the spillway channel floor and sides can significantly increase both the unit weight and uniaxial strength of the existing spillway materials with a corresponding reduction in fracture spacing and increase in layer thickness, thereby increasing their erosion resistance. In spillways where a vegetated channel is a project requirement, soil-cement stabilization of the subgrade of the channel can provide protection against excessive erosion while a placed and vegetated surface soil meets the aesthetic requirement. In the event of erosive flows, the placed soil surface may be removed, but the underlying stabilized subgrade acts as an erosion barrier.

In cases where the geology of the spillway channel is complex and the rock units change in physical character with changes in elevation or location or both, selective use of dental repair or strengthening may be required. It is important that dental fills placed in over-excavated areas, fractures, blast-damaged areas, and weak rock sites have similar physical properties as the remaining natural rock. For example, the use of concrete (4,500 psi) to fill holes in a weakly cemented sandstone (3,000 psi) simply reverses the weak rock-hard rock relationship and concentrates the erosive energy on the sandstone. It is also important that dental fills be keyed into the remaining bedrock using rebar or other ties. This reinforcement binds the patch to the bedrock and reduces the possibility that hydraulic forces will be able to lift and remove the patch. The use of rock bolts to tie together fractured rock while providing reinforcement to the repaired sections improves both the rock mass and genesis/tectonic properties of the spillway.

Many spillway channels have at least one knickpoint where the longitudinal profile increases abruptly. These geometric features may be caused by economic or geologic factors. In the case where the knickpoint is the result of economic choices in the design of the channel, some form of structural spillway, such as an ogee weir and stilling basin, should be considered for this area. In cases where the

knickpoint is the result of geologic factors or has developed following a period of flow in the channel, a detailed geologic evaluation of the site will be required. The longitudinal channel geometry at knickpoints is often nonplanar and contains smaller geometric anomalies that can strongly affect the erosion process.

Conceptual designs for the remediation of spillway erosion are shown in Figure 15. Note that the concepts attempt to match the repair with the existing geologic conditions so that there is a minimum impact on channel geometry and hydraulics.

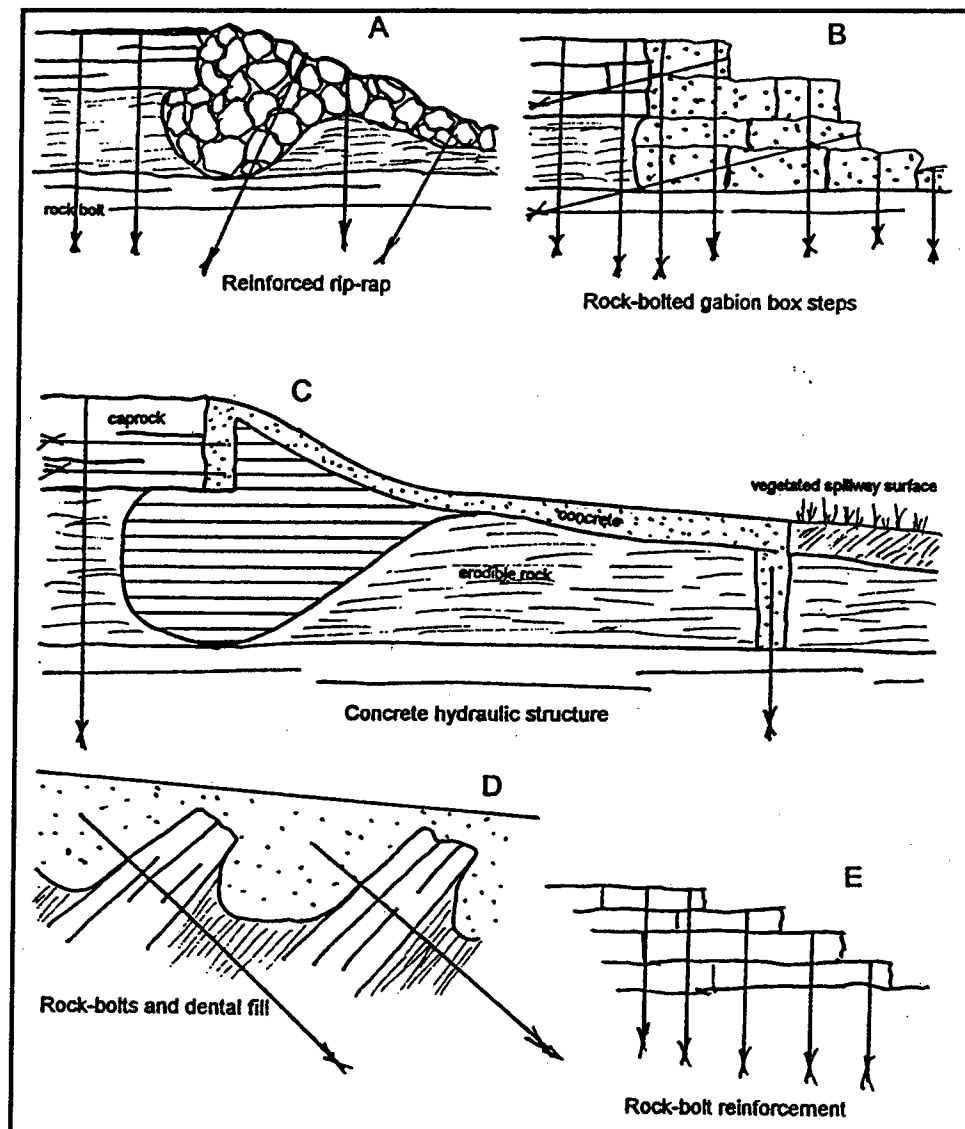


Figure 15. Conceptual designs for the remediation of various forms of spillway erosion: (A) use of large riprap reinforced with chain-link fence rock bolted into sound rock; (B) cobble-filled, gabion boxes rock bolted into place to form a series of small knickpoints; (C) reinforced concrete hydraulic structure and stilling basin to safely lower flows over knickpoint; (D) dental concrete, soil-cement or roller-compacted concrete filling eroded zones in dipping rocks and rock bolted into sound rock below; (E) rock bolt reinforcement in thinly bedded layered rocks to form a stable series of cataracts

References

- American Society of Civil Engineers/United States Committee On Large Dams. (1975). *Lessons from dam incidents, USA*. American Society of Civil Engineers, New York.
- _____. (1988). *Lessons from dam incidents, USA-II*. American Society of Civil Engineers, New York.
- Barton, N. (1988). "Rock mass classification and tunnel reinforcement selection using the q-system." *Rock classification systems for engineering purposes*. Kirkaldie, L., ed., ASTM STP 984, American Society for Testing and Materials, Philadelphia, 59-88.
- Bieniawski, Z.T. (1988). "The rock mass rating (RMR) system (geomechanics classification) in engineering practice." *Rock classification systems for engineering purposes*. Kirkaldie, L., ed., ASTM STP 984, American Society for Testing and Materials, Philadelphia, 17-34.
- Cameron, C.P., Cato, K.D., McAneny, C.C., and May, J.H. (1986). "Geotechnical aspects of rock erosion in emergency spillway channels," Technical Report REMR-GT-3, Report 1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Cameron, C.P., Patrick, D.M., Cato, K.D., and May, J.H. (1988). "Geotechnical aspects of rock erosion in emergency spillway channels, analysis of field and laboratory data," Technical Report REMR-GT-3, Report 2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Cato, K. D. (1991). "Performance of geological material under hydraulic stress," Ph.D diss., Texas A&M University, College Station, TX.
- Chow, V.T. (1959). *Open channel hydraulics*. McGraw-Hill, New York.
- Clemence, K.T. (1988). "Influence of stratigraphy and structure on knickpoint erosion," *Bulletin of the Association of Engineering Geologists* 25(1), 11-16.

- Golze, A.R. (1977). *Handbook of dam engineering*. Van Nostrand Reinhold, New York.
- Jenny, H. (1941). *Factors of soil formation*. McGraw-Hill Book Company, New York.
- Kirsten, H.A.D. (1988). "Discussion on rock material field classification procedure." *Rock classification systems for engineering purposes*. Kirkaldie, L., ed., ASTM STP 984, American Society for Testing and Materials, Philadelphia, 55-58.
- May, J.H. (1988). "Geologic and hydrodynamic controls on the mechanics of knickpoint migration," unpublished Ph.D diss., Texas A&M University, College Station, TX.
- Ralston, D.C., and Brevard, J.A. (1988). "SCS's 40 year experience with earth auxiliary spillways," presented at the *Fifth Annual Meeting: Association of State Dam Safety Officials*, Manchester, NH.
- Robinson, K.M. (1988). "Stress distribution at an overfall," Paper No. 88-2135, *Summer Meeting: American Society of Agricultural Engineers*, Rapid City, SD.
- _____. (1989). "Gully erosion in earth spillways," Paper No. 89-2057, *Summer Meeting: American Society of Agricultural Engineers*, Quebec, Canada.
- Smith, D.D., and Wischmeier, W.H. (1962). "Rainfall erosion." *Advances in agronomy* 14, 109-148.
- Soil Conservation Service. (1987a). "Rock material field classification procedures," Bulletin 210-VI, Technical Release 71, Second Ed., U.S. Department of Agriculture, Washington, DC.
- _____. (1987b). "Excavated rock spillway classification and layout," Geology Technical Note 4, Second Revision, U.S. Department of Agriculture, Chester, PA.
- Temple, D. (1989). "Mechanics of an earth spillway failure," Paper No. SWR-200, *Southwestern Regional Meeting: American Society of Agricultural Engineers*, Stillwater, OK.
- U.S. Army Corps of Engineers. (1965). "Hydraulic design of spillways," Engineer Manual No. 1110-2-1603, Office of the Chief of Engineers, Washington, DC.
- Woodward, R.C. (1985). "Geological factors in spillway terminal structure design," *Engineering Geology* 22, 61-70.

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